Open Issues on the Synthesis of Evolved Stellar Populations at Ultraviolet Wavelengths

Miguel Chavez • Emanuele Bertone

Abstract In this paper we briefly review three topics that have motivated our (and others') investigations in recent years within the context of evolutionary population synthesis techniques. These are: The origin of the FUV up-turn in elliptical galaxies, the age-metallicity degeneracy, and the study of the mid-UV rest-frame spectra of distant red galaxies. We summarize some of our results and present a very preliminary application of a UV grid of theoretical spectra in the analysis of integrated properties of aged stellar populations. At the end, we concisely suggest how these topics can be tackled once the World Space Observatory enters into operation in the midst of this decade.

Keywords ultraviolet: stars; ultraviolet: galaxies; galaxies: stellar content; galaxies: elliptical; galaxies: high redshift

1 Introduction

The study of stellar populations of non-resolved systems has greatly relied on the models derived from evolutionary populations synthesis technique. This approach is based on the spectrophometric properties of stars at, ideally, all evolutionary phases and takes into account all phenomena that largely affect the evolution of a star (e.g., mass-loss). Over the years, ever since the technique was first implemented (Tinsley 1968, 1972), a wide variety of models based on different ingredients have been constructed and used in the study of young and old stellar populations (among the most popular ones, Buzzoni 1989; Bressan, Chiosi & Fagotto

Miguel Chavez

Emanuele Bertone

Instituto Nacional de Astrofisica, Optica y Electronica, Luis E. Erro 1, 72840 Tonantzintla, Puebla, Mexico

1994; Worthey 1994; Bruzual & Charlot 1993, 2003; Leitherer et al. 1999; Maraston 2005). Not surprisingly, most of the work done up to date has vastly focused in the optical spectrophotometric properties of stellar systems, and until relatively recently it has expanded to other wavelengths (as far as the detailed analysis of spectral features is concerned), and, in some cases, included the effects of an interstellar medium (Silva et al. 1998; Panuzzo et al. 2005).

At ultraviolet (UV) wavelengths, usually divided into two segments, the far-UV (1200–2000 Å) and the mid-UV (2000–3200 Å), the natural systems to look at are those whose underlying populations copiously emit and have their emission maxima in that window, i.e. star-forming systems. While these systems are extremely important in many astrophysical contexts (see, e.g., Buzzoni 2002), it was eventually realized that also old and intermediate age populations, which will be the main subject in this paper, deserve attention by their own right. As an example we can mention the countless studies motivated by the unexpected finding of a prominent far-UV flux excess in the bulge of Andromeda (Code 1969). Aside of this far-UV flux excess, the mid-UV still remains vastly unexplored, in spite of the early suggestions that this wavelength region can help in lifting the so-called age-metallicity degeneracy (AMD) that plagues the optical spectrophotometric properties of evolved populations and that prevents the univocal determination of these parameters (Worthey 1994; Dorman et al. 2003). Disentangling the effects of age and chemical composition is particularly important when attempting to evaluate the characteristics of distant red objects for which, through optical observations only feasible with the current generation of large telescopes, we can only access the rest-frame mid-UV flux (e.g., Dunlop et al. 1996).

Motivated by these three issues inherent to aged populations, the nature of the far-UV flux, the AMD, and

the properties of instrisically red galaxies up to $z \sim 2$, we started a project aimed at providing complementary tools for their analysis. In what follows, we present a short (and necessarily incomplete) review of each of the above mentioned topics; we also briefly describe our project and present some preliminary results that are still under investigation.

2 The Far-UV Rising Branch of Elliptical Galaxies

Early-type stellar systems, such as elliptical galaxies and spiral bulges, are sometimes characterized by a prominent flux shortward of 2000 Å (Fig. 1). The nature of this flux excess (also called UV upturn, UVX phenomenon or UV rising branch) has been a subject of much debate ever since its discovery in the bulge of M31 (Code 1969). Soon after this detection, a variety of hypotheses emerged to explain the FUV rising flux (see the excellent reviews by Burstein et al. 1988; Greggio & Renzini 1990; O'Connell 1999): among them, a non-thermal origin through the galactic nuclear activity, the presence of an unexpected (for longly thought quiescent systems) population of hot young stars (Tinsley 1972), low-mass metal-rich evolved objects (Bressan, Chiosi & Fagotto 1994; Yi et al. 1997) or their metal-poor counterparts (Lee 1994). More recently, it has been analyzed the potential dominant role that subdwarf stars could play in modulating the far-UV properties of the host galaxy, either as members of binary systems (Han, Podsiadlowski & Lunas-Gray 2007, 2009) or arising from the evolution of single stellar objects (Napivotski 2008, 2009). A supplemental piece of the puzzle has been provided by the detection of multiple main sequences (MSs) in galactic globular clusters, which reinforces the explanation of UVX phenomenon through presence of helium-rich sub-populations.

Over the past four decades evidence has grown in favour of the low-mass star hypotheses. Hills (1971) argued against a non-thermal origin based on the overall shape of the far-UV energy distributions, which more closely resembles that of the Rayleigh-Jeans tail of a thermal source. Additionally, the diffuse distribution of the UV radiation, which can be fitted by a de Vaucouleurs profile such as the visible light, cannot be explained by the presence of a highly concentrated source, as would be expected if an active nucleus is the origin (Oke, Bertola & Capaccioli 1981; Ohl et al. 1998). In a similar way, the UV imaginery has also worked against the residual star formation hypothesis (which would be implied by the presence of hot MS stars) since, within the detection and resolution limits of several experiments, O and B stars have not yet been detected.
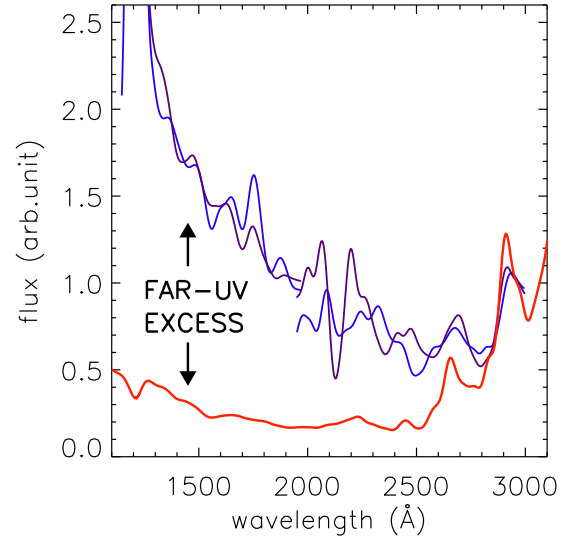

Fig. 1 Comparison of the mid-UV and far-UV spectral energy distribution of two elliptical galaxies observed with IUE (NGC1399 and NGC4649) to illustrate the far-UV excess. The violet and blue curves correspond to the observed spectra, broadened with a Gaussian kernel of 50 Å, and the red flux to a 10 Gyr old theoretical spectra of solar metallicity, calculated with the ingredients described in Chavez et al. (2009).

Whilst the currently most accepted picture for the nature of the far-UV excess is that the bulk of UV radiation is dominated by helium burning low mass stars and their progeny, in particular the so-called AGB-manqué, the idea of having on going star formation at very low levels has remained as a still plausible elucidation for the UVX phenomenon (Rich et al. 2005; Rich 2009). This fact might be supported by the prevalence of molecular hydrogen (usually traced by the more accessible signatures of carbon monoxide at millimeter wavelengths) in early-type systems, although in small amounts, indicative of star formation with an efficiency which is in fact similar to that found in spiral aggregates (e.g., Sage, Welch & Young 2007).

3 The Age-Metallicity Degeneracy

The optical colors of old populations are affected by the age-metallicity degeneracy (Worthey 1994): it implies that the spectrophotometric properties of an unresolved stellar population can not be distinguished from those of another population three times older and with half the metal content. As an example, we show, in Fig. 2, the comparison of the spectral energy distributions (SEDs) [calculated using the models of Worthey

$(1994)^1$ and normalized to the K band] of two simple stellar populations with ages and abundances indicated in the labels of the figure. In the lower planel, we display the flux residual in magnitudes of the two energy distributions.

Being arguably amongst the main parameters of a stellar population, there have been a number of studies aimed at finding the appropiate features(s) that unambiguously separate the effects of age from those of metallicity. In fact, Worthey (1994) conducted a detailed analysis of optical features in the form of spectrocopic indices (the so-called Lick indices) and found that akin the broad band colors, the indices, while partially diminishing the AMD, are also degenerate.

More recently, alternative spectral windows have been proposed as promising tools to lift the AMD. In particular, the rest-frame mid-UV flux and colors (Yi 2003; Dorman et al. 2003; Kaviraj et al. 2007) has been investigated on the basis that the UV properties are dominated by different stellar types at different evolutionary phases (MS) with respect to those dominating the optical (red giants). The overall results indicate that the UV indeed helps to better constrain the age of unresolved systems (as would be expected since the MS turn-off are much more sensitive to age than the red giant branch), but the determination of chemical composition was still better determined by the more sensitive optical features. The obvious path to further tackle the AMD problem was the use of mid-UV spectroscopic indices, however, there was the prevalent concept (somewhat justified, but quantitatively not investigated) that the use of synthetic UV indices at the appropiate resolution was still inadequate for the study of, for example, IUE spectra (see brief discussion in Chavez et al. 2007) and therefore investigations of absorption indices was conducted by using, for instance, Kurucz (1993) low resolution grid (e.g., Lotz et al. 2000), which appeared more reliable.

To date, the use of mid-UV synthetic indices is still in its infancy. Suffice here to mention that the citations to the relevant works where they were defined (Fanelli et al. 1990) are outnumbered by a factor of 15 (!) by the papers referencing the optical indices definition (Worthey et al. 1994), albeit they were defined roughly at the same time.
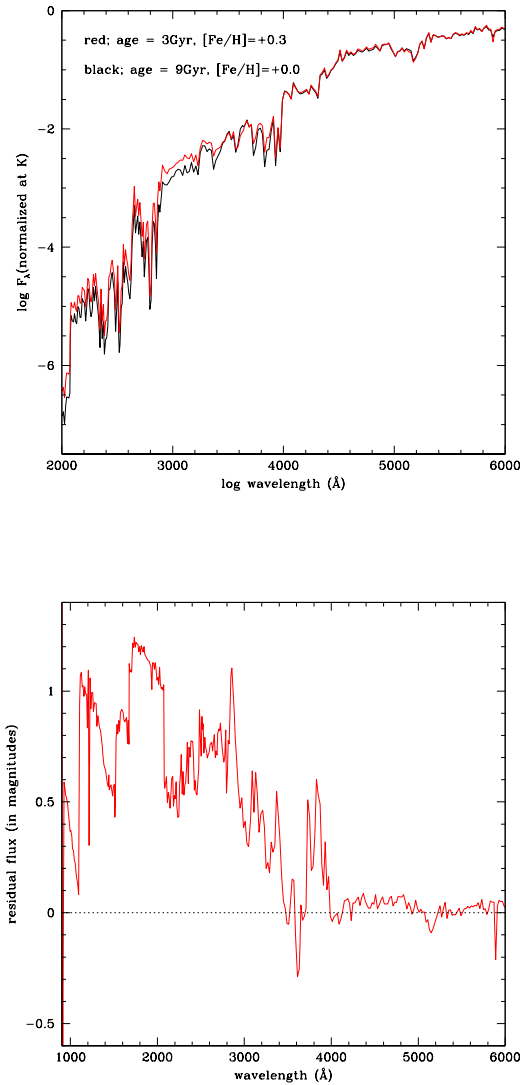
[1]through the on-line application *Dial a Galaxy*: http://astro.wsu.edu/worthey/

Fig. 2 An example of the age-metallicity degeneracy. In the upper panel we plot the spectral energy distributions (normalized to the K band), of two simple stellar populations for the ages and chemical compositions as labeled in the figure. We have used the models of Worthey (1994) for a Salpeter initial mass function. In the lower panel we display the flux residual in magnitudes of the SEDs. Note that while the differences are small in the optical interval, in the UV the residuals reach up to one magnitude, indicating that if the age-metallicity degeneracy is present in the UV it is necessarily different from that in the optical

4 Distant Red Galaxies

Observations at optical and infrared (IR) wavelengths of distant red[2] galaxies (up to redshift of $z \sim 2$) probe the rest-frame UV range, in particular the mid-UV. The first high z red galaxies detected were two faint radio sources from the Lieden-Berkeley Deep Survey (LBDS): LBDS 53W091 ($z =1.55$) and LBDS 53W069 ($z =1.43$) (Dunlop et al. 1996; Spinrad et al. 1997; Dunlop et al. 1999). The analysis of these systems was soon a subject of much debate. For instance, Spinrad et al. (1997) determined an age of 3.5 Gyr for LBDS 53W091, which posed complications to explain galaxy formation under an Einstein-De Sitter universe. This age was soon contested by a series of authors (Bruzual & Magris 1997; Heap et al. 1998; Yi et al. 2000) that derived much younger ages (<2 Gyr), which allowed for more comfortable estimates for the formation redshift (z_F) of the galaxies. Subsequent analyses revived the polemic by confirming the first determinations, i.e. ascribing ages in excess of 3 Gyr (Nolan et al. 2003; Ferreras & Yi 2004). Aside from the different methodologies used for the age determinations, it was clear that our poor knowledge of the UV spectrum of the presumably well understood MS stars (e.g., Peterson, Dorman & Rood 2001) was (and still is to some extent) a major drawback that has prevented the unambiguous determination of the main properties (age and chemical composition) of these distant systems.

More recently, a series of deep surveys have been conducted (Cimatti et al. 2002; Abraham et al. 2004; McCarthy et al. 2004) and now include well over 300 systems with similar spectrophotometric properties as those of the prototypical LBDS 53W091. Cimatti et al. (2008) presented what perhaps is the best spectrum representative of distant red objects. Within the Galaxy Mass Assembly ultra-deep Sky Survey (GMASS) program, they selected 13 passive galaxies (with $1.3 < z < 2.0$) on the basis of their red UV color, defined as the magnitude difference between two bands (each of 400 Å width) centered at 2900 and 3300 Å, and constructed a *stacked* spectrum that totalled nearly 500 hours of observing time at the Very Large Telescope. By comparing that spectrum with single stellar populations (SSPs) from several population synthesis codes (Bruzual & Charlot 2003; Maraston 2005), they determined, from the rest-frame UV alone, ages that ranged from 0.7 to 2.8 Gyr and metallicities in the range 0.2 to 1.5 $Z_\odot$. By adding to the comparison near and mid

IR photometric data, they significantly constrained the ages to 1–1.6 Gyr and found that $Z = Z_\odot$ provided the best results.

In Fig. 3, we show the GMASS *stacked* spectrum of the 13 red galaxies (black) together with three different SSPs of various ages and chemical compositions. As a qualitative demonstration of the AMD in the UV, we note that the observed spectrum is very similar to the middle two SSP fluxes constructed with quite different parameters.

It is beyond the scope of this paper to discuss any detail on the procedures so far delevoped to establish the age and chemical composition of distant systems. We, nevertheless, believe that in general the spectrophotometric analysis of distant objects has been carried out with stellar libraries that might be inadequate, in particular concerning the spectral resolution and capabilities of representing real stars.

5 Evolved Stellar Populations in the UV

Back in 2002 the Stellar Atmospheres and Populations Research Group (GrAPEs–for its designation in spanish) at the Instituto Nacional de Astrofísica, Óptica y Electrónica initiated a project aimed at providing updated stellar tools for the analysis of the UV spectra of a variety of stellar aggregates, mainly evolved ones. The overall project consists in four main steps, namely a)- the creation of a theoretical stellar database that we have called UVBLUE[3], b)- the comparison of such data base with observational stellar data, c)- the calculation of a set of synthetic SEDs of SSPs and their validation through a comparison with observations of a sample of Galactic globular clusters, d)- construction of models for dating local ellipticals and distant red galaxies. In Chavez (2009), we presented a summary of the results obtained in steps (a) and (b) and the reader is referred to that paper and the original references for a detailed description of the project (Rodriguez-Merino et al. 2005; Chavez et al. 2007). In what follows, we elaborate on the third step.

5.1 UV Spectroscopic Indices in Globular Clusters

In Chavez et al. (2009) we presented the first theoretical analysis of the UV integrated spectra of evolved SSPs (see also Maraston et al. 2009, for young populations). We focused on particular absorption lines and blends to establish, through the use of spectroscopic indices, their behavior in terms of age and chemical

---

[2]In the context of this paper, we ascribe red galaxies to the extremely red objects (EROs), that are intrinsically red, and not to the dust-enshrouded star-forming systems.
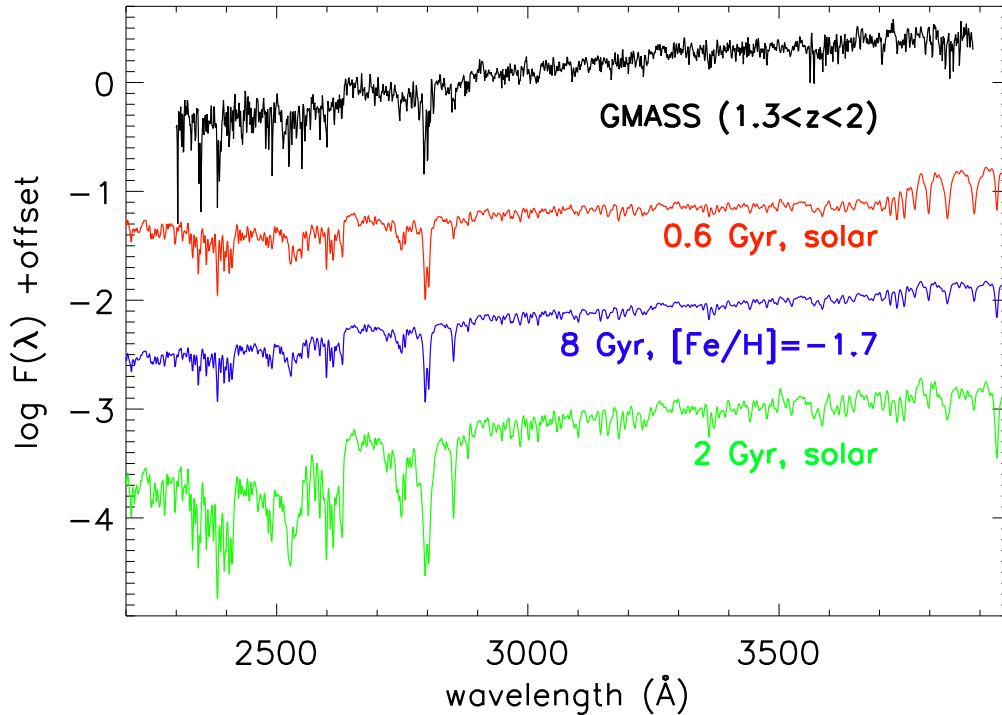
[3]http://www.inaoep.mx/∼modelos/uvblue/uvblue.html

Fig. 3 GMASS composite spectrum (in black) compared to three theoretical SSP energy distributions calculated with UVBLUE database and the synthesis code of Bressan, Chiosi & Fagotto (1994) with the updates described in Chavez et al. (2009). Qualitatively, high z galaxies can be well represented by either a very young (0.6Gyr) and solar metallicity or a rather old (8Gyr) subsolar ([M/H]=-1.7) populations

composition. We identified several interesting tendencies, such as the low general sensitivity of the indices to age and the remarkably distinct behavior of the indices Fe II 2332 and Fe II 2402, at super solar regimes (in fact, we propose these indices as a promising tool to establish the age in metal-rich systems). Synthetic indices were compared to IUE low resolution observations of prototypical simple populations, i.e. globular clusters, and the results were highly encouraging, indicating that theoretical SSPs might be confidently used in the analysis of more complex systems. There were two additional results that will be important in future analyses: we quantitatively showed that the presence of hot stars (e.g., blue stragglers and blue horizontal branch (B-HB) objects, which, by the way, are among the main contributors to the far-UV rising branch) can significantly dilute the mid-UV absorption indices, and that the enhancement of α-elements considerably modifies the overall SED of evolved populations.

Based on the results obtained so far, the project at its current stage is now focusing on the detailed analysis of local (mostly based on IUE observations) and distant evolved systems. This study will include, in a similar way as Cimatti et al. (2008), two steps: we are first conducting a UV analysis that will be later followed by a panchromatic study using, for instance, the modelling

machinery developed by Panuzzo et al. (2005). We are also carrying out a detailed study of the far-UV indices and its validation process (as we did in the mid-UV) with the main goal of determining the metallicity of the objects responsible of the far-UV up turn.

5.2 The Sun, M32, and Distant Red Galaxies from a Purely UV Perspective

In Bertone & Chavez (2009), we presented a preliminary study of the mid-UV spectra of the Sun and M32 and determined, through a χ_ν^2 analysis, their age and chemical composition. Briefly, this analysis consisted in comparing the observed SEDs of the Sun, extracted from the UARS/SUSIM archive[4], and that of M32, taken with the Faint Object Spectrograph onboard the Hubble Space Telescope (program 1D=6636; PI: M. Gregg), to a set of theoretical integrated spectra calculated with the synthesis code developed by Buzzoni (1989). In the synthesis code, we have incorporated the UVBLUE stellar library and considered a red HB morphology with a Salpeter initial mass function (s=2.35).

The results are listed in Table 5.2 (see Bertone & Chavez 2009, for more details). Interestingly, we obtained that

---

[4]http://daac.gsfc.nasa.gov/data/dataset/UARS/SUSIM

for the Sun (or, equivalently, for a population whose mid-UV spectrum is dominated by stars like the Sun), the absolute chi-square minimum is found for the solar metallicity and an age of 10.1 Gyr. This result is in remarkably good agreement with the solar age at the turn-off (e.g., Jorgensen 1991, 10.5 Gyr). Similarly, for the central region of M32 we found a *best* fiducial age for the stellar population of the central region of M32 of 3.64 Gyr, at solar metallicity. This result is, again, in quite good agreement with the generally accepted age of 3–4 Gyr at solar (or slightly super-solar) metallicity (see, e.g., Worthey 2004; Schiavon et al. 2004).

We have to note, however, that even though we obtained a "best value", in many instances, it is difficult to assess the significance of the difference of the minimum χ^2_ν values at the different metallicities. For example, the lowest χ^2_ν for Z=0.01, solar, and 0.03 for M32 are quite similar. Moreover, these results indicate that the small difference in the metal content between Z=0.01 and 0.017 produces a tremendous shift in the age of about 10 Gyr. This indicates that the age-metallicity degeneration is clearly present in UV spectra of stellar systems and, as mentioned before, operates in a different manner with respect to the optical.

A provocative exercise is to try to determine the age and chemical composition of distant ellipticals from a similar analysis, this is, solely based on their mid-UV spectrum. One of course can brandish that a panchromatic analysis (UV+optical+IR) should lead to an unambiguous determination of the parameters. Nevertheless, allow us, for now, to assume that we can not complement our UV data with optical and IR (or (sub)-mm data) as might be the case for the distant EROs for which we only have the IR fluxes (used for their selection from the surveys). Let us also assume that the UV light is indeed dominated by MS stars at the turn-off, as would be expected for systems such as globular clusters with red-clumped HBs or galaxies devoid of field counterparts of B-HB stars and their progeny. In other words, the global shape of the SEDs is not modified and the mid-UV spectroscopic indices are not diluted by the presence of hotter stars than the MS turn-off. This latter assumption might be tested with the measurement of the excess in the far-UV. Let us finally take for granted that the co-added spectrum depicted in Fig. 3 is representative of distant single objects.

Figure 4 shows the χ^2_ν distribution vs. age for the GMASS spectrum. For the analysis of this spectrum we have used the synthesis code of Bressan, Chiosi & Fagotto (1994) with the updates described in Chavez et al. (2009). The metallicities considered for this case range from Z=0.0004 to 0.05 (as labelled in the figure). The reason for using this code is that it includes younger

Table 1 Age and metallicity for the SUN and M 32.

Z	Sun Age (Gyr)	χ^2_ν	M 32 Age (Gyr)	χ^2_ν
0.0001	9.575	4347.0	10.000	153.9
0.001	15.000	2542.6	15.000	84.7
0.010	15.000	82.6	13.040	19.5
0.017	$10.115^{+1.620}_{-1.255}$	8.9	$3.640^{+0.725}_{-0.440}$	14.3
0.03	$7.465^{+1.210}_{-0.995}$	9.9	$2.790^{+0.515}_{-0.545}$	15.1
0.1	6.000	57.6	6.000	82.2

ages (<2 Gyr) than that of Buzzoni (1989). The analysis indicates (see results in Table 2) that the smallest χ^2_ν is obtained for an age of 2.40 Gyr and a chemical composition of Z=0.004. Nevertheless, analogously to the trends found for the Sun and M32, the minima are still more uneffective to segregate which of the results is more reliable.

At present, we are conducting the detailed analysis of the full sample of elliptical galaxies observed by IUE and instrisically distant red objects. The aim is not only to test other statistical methods (aside from the reduced χ^2_ν), but to also test the validity of the different assumptions upon which the studies can de carried out.

6 A Wish List for the World Space Observatory-UV

In the context of what we have discussed above, the WSO-UV (Shustov et al. 2009) will undoubtedly impact our knowledge on the UV properties of evolved populations. With its large aperture (as compared to its UV predecesors) and enhanced detectors sensitivities will:

- Significantly increase the quality (and quantity) of stars enabling us to construct a robust empirical database. As quoted by Chavez et al. (2007) and Maraston et al. (2009), the IUE stellar library has prevailed as the most complete for the analyses of

Table 2 Best fit parameters for GMASS galaxies

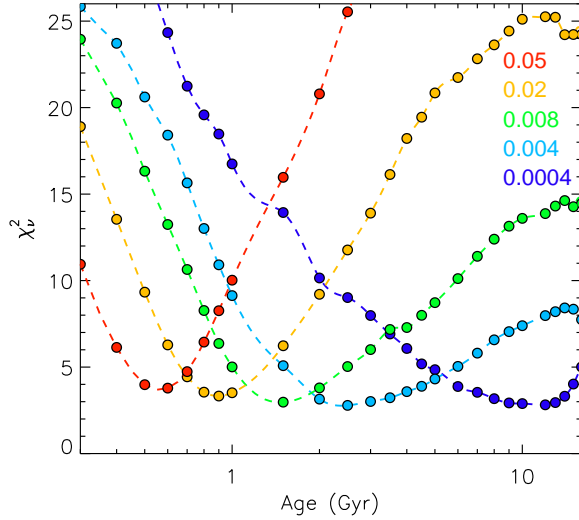| Z	Age (Gyr)	χ^2_ν
0.0004	11.75	2.81
0.0040	2.40	2.77
0.0080	1.45	2.96
0.0200	0.90	3.32
0.0500	0.55	3.69

Fig. 4 Distribution of χ^2_ν vs. age at different metallicities for the composite GMASS spectrum of Cimatti et al. (2008). Different colors stand for five different metallicities, as described in the figure label.

stellar aggregates. We, however, badly need to cope with the pausity in the coverage of the parameter space, particularly the metallicities.

- Increase the number of globular clusters (and old open clusters) to re-test the adequacy of SSP models. Of fundamental importance will be to empirically judge the effects of non solar-scaled abundances and to better assess the impact of the horizontal branch morphology on mid-UV spectroscopic indices.
- Cast light on the nature of the objects giving rise to the far-UV up-turn. At this wavelength the IUE-archive includes a rather small number of elliptical galaxies and none with data of enough quality to firmly establish the chemical composition of the undelying population of hot stars in these systems.

References

Abraham, R. G., et al. 2004, Astron. J., 127, 2455

Bertone, E., & Chavez, M. 2009, *Rev. Mex. Astron. & Astrophys.*, serie de conferencias, 37, 147

Bressan, A., Chiosi, C., & Fagotto, F. 1994, Astrophys. J., 94, 63

Bruzual, G., & Charlot, S. 1993, Astrophys. J., 405, 538

Bruzual, G., & Charlot, S. 2003, Mon. Not. R. Astron. Soc., 344, 1000

Bruzual, G., & Magris, G. C. 1997, in "The Ultraviolet Universe at Low and High Redshift, AIP, 408, 291

Burstein, D., Bertola, F., Buson, L., Faber, S. M., & Lauer, T. R., 1988, Astrophys. J., 328, 440

Buzzoni A. 1989, ApJS, 71, 817

Buzzoni, A. 2002, Astron. J., 123, 1188

Cimatti, A., et al. 2002, Astron. Astrophys., 392, 395

Cimatti, A., et al. 2008, Astron. Astrophys., 482, 21

Code, A. D. 1969, Publ. Astron. Soc. Pac., 81, 475

Chavez, M. 2009, Astrophys. Space Sci., 320, 45

Chavez, M., Bertone, E., Buzzoni, A., Franchini, M., Morossi, C., Malagnini, M. L. & Rodriguez-Merino, L. H., 2007, Astrophys. J., 657, 1046

Chavez, M., Bertone, E., Morales-Hernandez, J. & Bressan, A., 2009, Astrophys. J., 700, 694

Dorman, B., O'Connell, R. W., & Rood, Robert T., 2003, Astrophys. J., 591, 878

Dunlop, J. S., Peakock, J. A., Spinrad, H., Dey, A., Jimenez, R., Stern, D., & Windhorst, R. 1996, *Nature*, 381, 581

Donlop, J. S. 1999, proceedings of the conference The Most Distant Radio galaxies, Royal Netherlands Academy of Arts. H. J. A. Rottgering, P. N. Best & M. D. Lehnert eds. p. 71.

Fanelli, M. N., O'Connell, R. W., Burstein, D., & Wu, C. 1990, Astrophys. J., 364, 272

Ferreras, I., & Yi, S. K. 2004, Mon. Not. R. Astron. Soc., 350, 1322

Greggio, L., & Renzini, A. 1990, Astrophys. J., 364, 35

Han, Z., Podsiadlowski, P., & Lynas-Gray, A. E. 2007, Mon. Not. R. Astron. Soc., 380, 1098

Han, Z., Podsiadlowski, P., & Lynas-Gray, A. E. 2009, in New Quests in Stellar Astrophysics II. The Ultraviolet Properties of Evolved Populations, Astrophys. Space Sci.proceedings, ed. M Chavez, et al. (New York: Springer), 59

Heap, S. R., et al. 1998, Astrophys. J., 492, L31

Hills, J. G. 1971, Astron. Astrophys., 12, 1

Jorgensen U.G. 1991, A&A, 246, 118

Kaviraj, S., Rey, S. C. Rich, R. M. et al. 2007, Mon. Not. R. Astron. Soc., 381, L74

Kurucz, R. L. 1993, CDROM 13, ATLAS9 stellar atmosphere programs and 2km/s Grid

Lee, Y. W. 1994, Astrophys. J., 430, L113

Leitherer, K., et al. 1999, Astrophys. J. Suppl. Ser., 123, 3

Lotz, J. M., Ferguson, H. C., & Bohlin, R. C. 2000, Astrophys. J., 532, 830

Maraston, C. 2005, Mon. Not. R. Astron. Soc., 362, 799

Maraston, C. et al. 2009, Astron. Astrophys., 493, 425

McCarthy, P., et al. 2004, Astrophys. J. Lett., 614, L9

Napivotski, R., 2008, ASPC, 392, 139

Napivotski, R., 2009, in New Quests in Stellar Astrophysics II. The Ultraviolet Properties of Evolved Populations, Astrophys. Space Sci.proceedings, ed. M Chavez, et al. (New York: Springer), 191

Nolan, L. A., et al. 2003, Mon. Not. R. Astron. Soc., 341, 464

O'Connell R. W. 1999, Annu. Rev. Astron. Astrophys., 37, 603

Ohl, R. R. et al. 1998, Astrophys. J., 505, 11

Oke, J. B., Bertola, F., & Capaccioli, M. 1981, Astrophys. J., 243, 453

Panuzzo, P., Silva, L., Granato, G. L., Bressan, A., & Vega, O. 2005, AIPC, 761, 187

Peterson, R. C., Dorman, B., & Rood, R. T. 2001, Astrophys. J., 559, 372

Rich, R. M. 2005, et al. 2005, Astrophys. J., 619, L107

Rich, R. M. 2009, in New Quests in Stellar Astrophysics II. The Ultraviolet Properties of Evolved Populations, Astrophys. Space Sci.proceedings, ed. M Chavez, et al. (New York: Springer), 35

Rodriguez-Merino, L. H., Chavez, M., Bertone, E., & Buzzoni, A. 2005, Astrophys. J., 626, 411

Sage, L. J., Welch, G. A., & Young, L. M. 2007, Astrophys. J., 657, 232

Schiavon R. P., Caldwell N., Rose J.A. 2004, AJ, 127, 1513

Shustov, B., Sachkov, M., Gomez de Castro, A. I., et al. 2009, Astrophys. Space Sci., 320, 187

Silva, L., Granato, G. L., Bressan, A., & Danese, L. 1998, Astrophys. J., 509, 103

Spinrad, H., Dey, A., Stern, D., Dunlop, J. S., Peacock, J. A., Jimenez, R., & Windhorst, R. 1997, Astrophys. J., 484, 581

Tinsley, B. M. 1968, Astrophys. J., 151, 547

Tinsley, B. M. 1972, Astrophys. J., 178, 319

Worthey, G. 1994, Astrophys. J. Suppl. Ser., 95, 107

Worthey, G., Faber, S. M., Gonzalez, J. J., & Burstein, D. 1994, Astrophys. J. Suppl. Ser., 94, 687

Worthey G. 2004, AJ, 128, 2826

Yi, S. K, et al. 2000, Astrophys. J., 533, 670

Yi, S. K. 2003, Astrophys. J., 582, 202

Yi, S. K., Demarque, P., & Oemler, A. J. 1997, Astrophys. J., 486, 201